PROPERTIES OF LIGHT

Goal: To understand the fundamental properties of light

Objectives (as defined by the Utah State Core Curriculum):

- Kindergarten
    - Objective 3 Develop and use skills to communicate ideas, information, and feelings.

      2. Recognize similar colors as being members of the family of reds, blues, and yellows and shapes as being similar to squares, circles, and triangles.

- 3rd Grade. Science Benchmark: *Light is produced by the sun and observed on Earth. Living organisms use heat and light from the sun. Heat is also produced from motion when one thing rubs against another. Things that give off heat often give off light. While operating, mechanical and electrical machines produce heat and/or light.*
    - Objective 2: Demonstrate that mechanical and electrical machines produce heat and sometimes light.

      2. List examples of mechanical or electrical devices that produce light.

- 6th Grade. Science Benchmark: *Heat, light, and sound are all forms of energy. Heat can be transferred by radiation, conduction and convection.* ***Visible light can be produced, reflected, refracted, and separated into light of various colors.*** *Sound is created by vibration and cannot travel through a vacuum. Pitch is determined by the vibration rate of the sound source.*

- Standard VI: Students will understand properties and behavior of heat, **light**, and sound.
    - Objective 2: Describe how light can be produced, reflected, refracted, and separated into visible light of various colors.

      1. Compare light from various sources (e.g., intensity, direction, color).
      2. Compare the reflection of light from various surfaces (e.g., loss of light, angle of reflection, reflected color).
      3. Investigate and describe the refraction of light passing through various materials (e.g., prisms, water).
      4. Predict and test the behavior of light interacting with various fluids (e.g., light transmission through fluids, refraction of light).
      5. Predict and test the appearance of various materials when light of different colors is shone on the material.

Introduction

Scientists have long been intrigued by the nature of light, and philosophers have had endless arguments concerning the proper definition and perception of light. It is important to understand the nature of light because it is **the** source of energy to support life on earth. Plants convert light energy from the sun to chemical energy through photosynthesis. Light is the means by which we are able to transmit and receive information from objects around us and throughout the universe.

The nature and properties of light have been subjects of great interest and speculation since ancient times. The Greeks believed that light consisted of tiny particles (corpuscles) that were emitted by a light source and stimulated visual perception upon striking the observer's eye. It is easy to see why they would have thought this due to the fact that light travels in straight lines and bounces off a mirror much like a ball bouncing off a wall. No one had actually seen these particles of light, but there were several possible explanations as to why that might be. For example, the particles could be too small, or moving too fast, to be seen, or perhaps our eyes see right through them. Newton used this corpuscular theory to explain the reflection and refraction of light.

In 1670 one of Newton's contemporaries, the Dutch scientist Christian Huygens, was able to explain many properties of light by proposing that light was wave-like in character (i.e. waves transfer energy, not particles). In 1801 Thomas Young showed that light beams can interfere with one another, giving strong support to the wave theory. In 1856 Maxwell developed a brilliant theory that electromagnetic waves travel with the speed of light. By this time the wave theory of light seemed to be on solid ground. However, at the beginning of the 20^{th} century Max Plank and Albert Einstein returned to the corpuscular theory of light in order to explain how radiation is emitted by hot objects and how electrons are emitted by a metal exposed to light (i.e. the photoelectric effect).

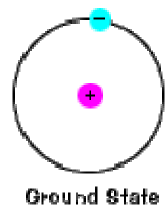
Today scientists believe that light can behave as both a particle and a wave, but they also recognize that either view is a simple explanation for something more complex. Experiments can be devised which will display either its particle-like or its wave-like nature. It is the nature and character of light which we will discuss during this workshop.

What is Light?

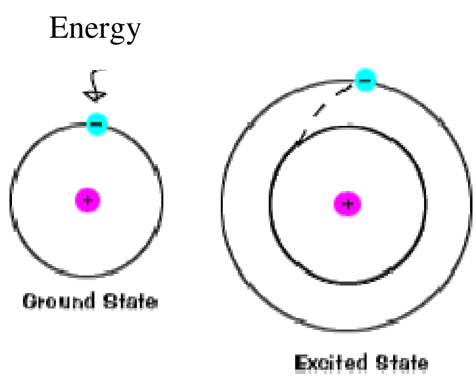
Any light that you see is made up of a collection of one or more photons (a photon is …) propagating through space as electromagnetic waves. In total darkness, our eyes are actually able to sense single photons, but generally what we see in our daily lives comes to us in the form of zillions of photons produced by light sources and reflected off objects. If you look around you right now, there is probably a light source in the room producing photons, and objects in the room that reflect those photons. Your eyes absorb some of the photons flowing through the room, and that is how you see.

There are many different ways to produce photons, but all of them use the same mechanism inside an atom to do it. This mechanism involves the energizing of electrons orbiting each atom's nucleus. Electrons circle the nucleus in fixed orbits -- a simplified way to think about it is to imagine how satellites orbit the Earth. There's a huge amount of theory around electron orbitals, but to understand light there is just one key fact to understand: An electron has a natural orbit that it occupies, but if you energize an atom you can move its electrons to higher orbitals. A photon of light is produced whenever an electron in a higher-than-normal orbit falls back to its normal orbit. During the fall from high-energy to normal-energy, the electron emits a photon -- a packet of energy -- with very specific characteristics. The photon has a frequency, or color, that exactly matches the distance the electron falls.

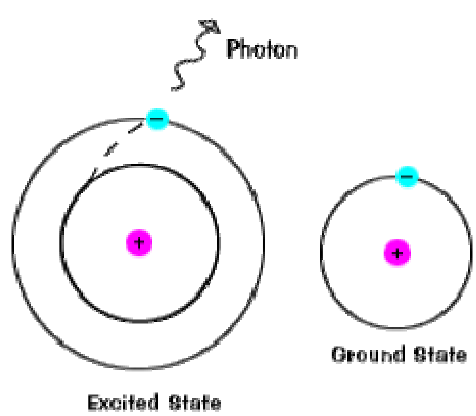
1. A normal electron at the ground state energy level.



2. The addition of energy excites the electron and it bumps-up to a higher energy level.



3. The exited electron releases energy in the form of a photon and returns back to its ground state. We perceive the photon as light when it enters the eye.



Probably the most common way to energize atoms is with heat, and this is the basis of incandescence. If you heat up a horseshoe with a blowtorch, it will eventually get red hot, and if you heat it enough it gets white hot. Red is the lowest-energy visible light, so in a red-hot object the atoms are just getting enough energy to begin emitting light that we can see. Once you apply enough heat to cause white light, you are energizing so many different electrons in so many different ways that all of the colors are being generated -- they all mix together to look white.

Heat is the most common way we see light being generated -- a normal 75-watt incandescent bulb is generating light by using electricity to create heat. However, there are lots of other ways to generate light, here a few examples:

- **Halogen lamps** - Halogen lamps use electricity to generate heat, but benefit from a technique that lets the filament run hotter because the filament is contained within a halogen gas (i.e. Fluorine, Chlorine, Bromine, Iodine, Astatine).
- **Gas lanterns** – A gas lantern uses a fuel like kerosene or propane as the source of heat. This heat energizes elements in the lantern mantle (such as thorium), which gives off light.
- **Fluorescent lights** – Fluorescent lights use electricity to directly energize atoms without requiring heat. Fluorescent lights work by using a filament to energize mercury atoms. Mercury releases this energy as ultraviolet light. The ultraviolet light then excites atoms in the phosphor coating on the inside of the glass tube, which in turn releases its energy as white light.
- **Glow-in-the-dark**– In a glow-in-the-dark object the electrons are energized (usually by being exposed to light) but fall back to lower-energy orbitals over a long period of time, so the object can glow for an extended time (usually less than 3 hours).

  One unique type of glow-in-the-dark technology uses tritium (H_3O) atoms to provide the energy to the glow-in-the-dark coating, thus eliminating the need to expose the material to sunlight. Tritium devices glow 100 times brighter than conventional glow-in-the-dark coatings and will glow continuously for over 25 years. Tritium watches are primarily designed for pilots and SCUBA divers.

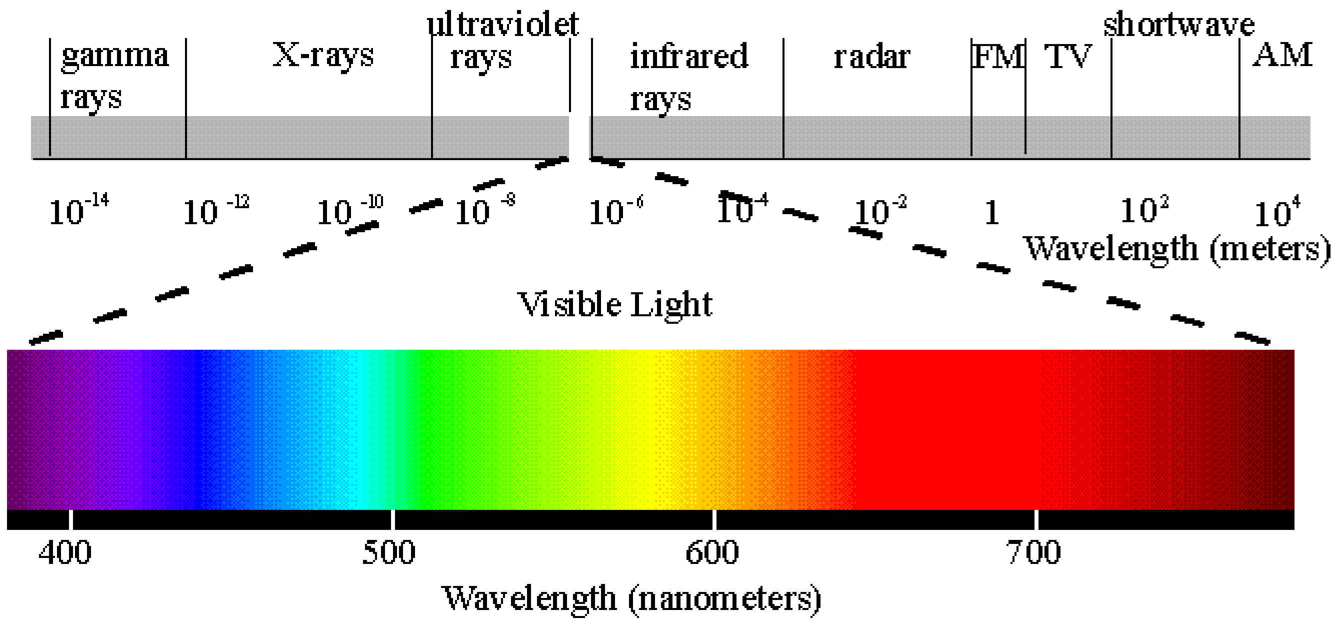
- **Indiglo watches** - Indiglo watches use electricity to directly energize phosphor atoms and produce light similar to the way fluorescent lights do, only without the intermediate step of energizing mercury.
- **Chemical light sticks** - A chemical light stick use a chemical reaction to energize atoms. It is interesting to note that fireflies perfected this technology long before man ever conceived of such an idea.

The thing to note from this list is that *anything* that produces light does it by energizing atoms in some way.

Making Colors

Visible light is a very small part of the electromagnetic spectrum that can be perceived by the human eye.

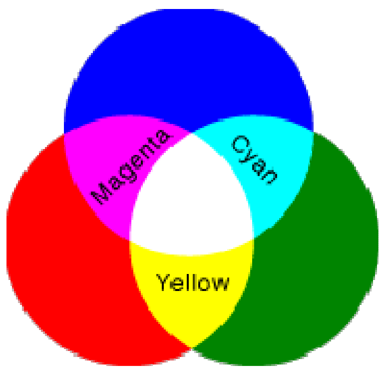
The Electromagnetic Spectrum



When you look at the visible light of the sun, it appears to be colorless, which we call white. Although we can see this light, white is not considered to be part of the visible spectrum. This is because white light is not the light of a single color, or frequency. Instead, it is made up of many color frequencies. Isaac Newton was the first person to demonstrate this. Newton passed sunlight through a glass prism to separate the colors into a rainbow spectrum. He then passed the “rainbow light” through a second prism and recombined the colors to produce white light. This proved conclusively that white light is a mixture of colors, or a mixture of light of different frequencies. The combination of every color in the visible spectrum produces a light that is colorless, or white. The colors

of the spectrum are red, orange, yellow, green, blue, indigo, and violette. These colors can be remembered using the well know acromym “Roy G. Biv”

Though the spectrum contains all known colors, there are three colors that dominate: red, green, and blue. These three are formally known as the *primary* colors of light (note that this may be different than what you learned in art, where the primary colors were red, yellow, and blue, more on this later). Using various combinations of these primary colors it is possible to make any color in the spectrum. Combining any two primary colors produces the *secondary* colors as follows:, red + green → yellow, blue + green → cyan, red + blue → magenta. Mixing all three primary colors produces white light. These combinations are shown in the illustration below.



- **Colors by Addition** - You can demonstrate the above illustration with three flashlights and three different colors of cellophane -- red, green and blue (commonly referred to as RGB). Cover one flashlight with one to two layers of red cellophane and fasten the cellophane with a rubber band (do not use too many layers or you will block the light from the flashlight). Cover another flashlight with blue cellophane and a third flashlight with green cellophane. Go into a darkened room, turn the flashlights on and shine them against a wall so that the beams overlap, as shown below. Where red and blue light overlap, you will see magenta. Where red and green light overlap, you will see yellow. Where green and blue light overlap, you will see cyan. You will notice that white light can be

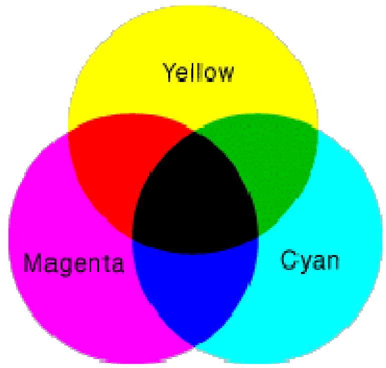
made by various combinations, such as yellow with blue, magenta with green, cyan with red, and by mixing all of the colors together.

By adding various combinations of red, green and blue light, you can make all the colors of the visible spectrum. This is how computer monitors (RGB monitors) produce colors (see PowerPoint demonstration activity).

- **Colors by Subtraction** - Another way to make colors is to absorb some of the frequencies of light, and thus remove them from the white light combination. The absorbed colors are the ones you will not see -- you see only the colors that come bouncing back to your eye. This is what happens with paints and dyes. The paint or dye molecules absorb specific frequencies and reflect others. The reflected frequency (or frequencies) is what you see as the color of the object. For example, the leaves of green plants contain a pigment called chlorophyll, which absorbs the blue and red colors of the spectrum but reflects green.

Here is an absorption experiment that you can try: Take a banana and the blue cellophane-covered flashlight you made earlier. Go into a dark room, and shine the blue light on the banana. What color is it? If you shine blue light on a yellow banana, the yellow should absorb the blue frequency; and, because the room is dark, there is no yellow light reflected back to your eye. Therefore, the banana appears black.

When making colors by subtraction there are again three dominant colors: yellow, cyan and magenta. These three are known as the *primary* pigments (recall that they were secondary colors). Combining two primary pigments produces the *secondary* pigments of red (magenta + yellow), blue (cyan + magenta), and green (cyan + yellow). (recall that these were the primary colors of light). Black is a special case in which all of the colors are absorbed. You can make black by combining yellow with blue, cyan with red or magenta with green. These particular combinations ensure that no frequencies of visible light can bounce back to your eyes.



The color scheme shown above appears to go against what you learned in art class about mixing colors, right? If you mix yellow and blue crayons, you get green, not black. This is because artificial pigments, such as crayons, are not perfect absorbers -- they do not purely absorb all colors but one. A "yellow" crayon can absorb blue and violet while reflecting red, orange and green. A "blue" crayon can absorb red, orange and yellow while reflecting blue, violet and green. So when you combine the two crayons, all of the colors are absorbed except for green. Therefore, you see the mixture as green, instead of the black demonstrated above.

As stated in the previous section, a computer monitor used red, green, and blue (RGB) to make colors on screen. Printers, on the other hand, use pigments or dies to make colors. Because paper does not emit light, we have to use pigments to absorb certain colors in order to see what we need on paper, thus your printer cartridge uses inks of the primary pigments yellow, cyan, and magenta (YCM).

To summarize, there are two basic ways by which we can see colors. Either an object can directly emit light waves in the frequency of the observed color, or an object can absorb all other frequencies, reflecting back to your eye only the light wave, or combination of light waves, that appears as the observed color. For example, to see a yellow object, either the object is directly emitting light waves in the yellow frequency, or it is absorbing the blue part of the spectrum and reflecting the red and green parts back to your eye, which perceives the combined frequencies as yellow.

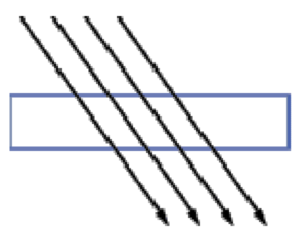
When Light Hits an Object

When a light wave hits an object, what happens to it depends on 1) the energy of the light wave, 2) the natural frequency at which electrons vibrate in the material, and 3) the strength with which the atoms in the material hold on to their electrons. Based on these three factors, four different things can happen when light hits an object:

- The waves can pass through the object with no effect. Objects which transmit all light are defined as *transparent*.
- The waves can be absorbed by the object. Objects which absorb all light are defined as *opaque*.
- The waves can be *reflected* or scattered off the object.
- The waves can be *refracted* through the object.

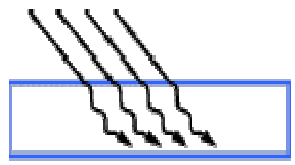
Transmittance

If the frequency or energy of the incoming light wave is slightly above or below the frequency needed to make the electrons in the material vibrate, then the electrons will not capture the energy of the light, and the wave will pass through the material unchanged. As a result, the material will be transparent to that frequency of light.



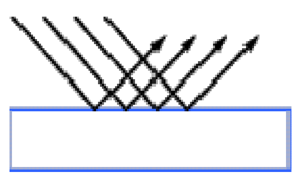
Absorption

In absorption, the frequency of the incoming light wave is at or near the vibration frequency of the electrons in the material. The electrons take in the energy of the light wave and start to vibrate. What happens next depends upon how tightly the atoms hold on to their electrons. Absorption occurs when the electrons are held tightly, and they pass the vibrations along to the nuclei of the atoms. This makes the atoms speed up, collide with other atoms in the material, and eventually give up the energy in the form of heat.



Reflection

The atoms in some materials hold on to their electrons loosely. In other words, the materials contain many free electrons that can jump readily from one atom to another within the material. When the electrons in this type of material absorb energy from an incoming light wave, they do not pass that energy on to other atoms. The energized electrons merely vibrate and then send the energy back out of the object as a light wave with the same frequency as the incoming wave. The overall effect is that the light wave does not penetrate deeply into the material. In most metals, electrons are held loosely, and are free to move around, so these metals reflect visible light and appear to be shiny.



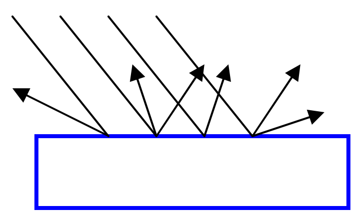
Understanding absorption and reflection helps to explain why we wear certain colors of clothes at different times of the year. In winter wearing dark colored clothes

helps you keep warm by absorbing light from the sun and converting it to heat. During the summer you can keep cool by wearing white or light-colored clothes that reflect the energy from the sun.

Scattering

Scattering is merely reflection off a rough surface. Incoming light waves get reflected at all sorts of angles, because the surface is uneven. The surface of paper is a good example. You can see just how rough it is if you look at it under a microscope. When light hits paper, the waves are reflected in all directions. This is what makes paper so incredibly useful -- you can read the words on a printed page regardless of the angle at which your eyes view the surface.

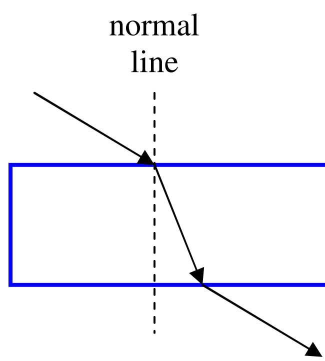
Another interesting rough surface is Earth's atmosphere. You probably don't think of the atmosphere as a surface, but it is considered "rough" to incoming white light. The atmosphere contains molecules of many different sizes, including nitrogen, oxygen, water vapor and various pollutants. This assortment scatters the higher energy light waves, the ones we see as blue light. This helps explain why the sky appears blue during the day. If the blue light was not reflected the sky would appear dark.



For a great demonstration and explanation of why the sky looks blue at mid-day and red at night go to http://scifun.chem.wisc.edu/HomeExpts/BlueSky.html .

Refraction

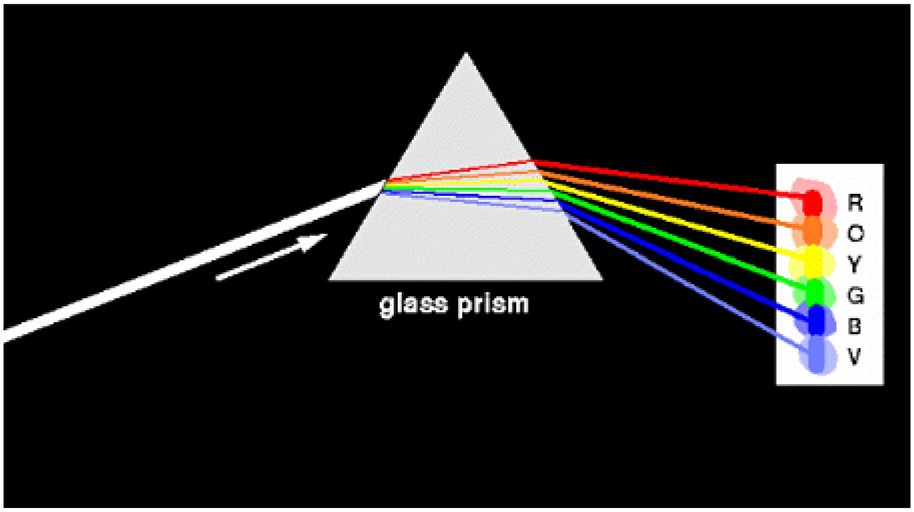
Refraction occurs when the energy of an incoming light wave matches the natural vibration frequency of the electrons in a material. The light wave penetrates deeply into the material, and causes small vibrations in the electrons. The electrons pass these vibrations on to the atoms in the material, and they send out light waves of the same frequency as the incoming wave. But this all takes time. The part of the wave inside the material slows down, while the part of the wave outside the object maintains its original frequency. This has the effect of bending the portion of the wave inside the object toward what is called the *normal line*, an imaginary straight line that runs perpendicular to the surface of the object. As the light ray exits the material it is again bent, only this time it is bent away from normal and exits at the same angle as it originally entered.



The amount of bending, or angle of refraction, of the light wave depends on how optically "dense" the material is and how much it slows down the light. It is this refraction of light that gives diamonds, topaz, opals, and various other gems their brilliance and color.

Making a rainbow

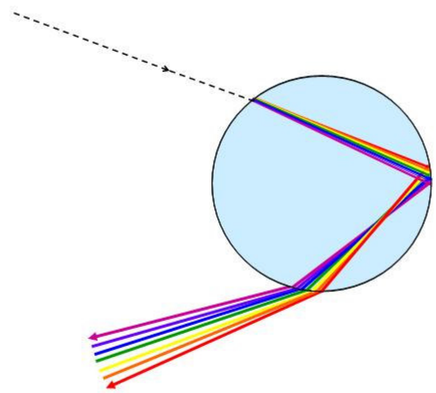
One interesting note about refraction is that light of different frequencies, or energies, will bend at slightly different angles. As white light enters a prism the various colors refract at different rates based on the amount of energy they have.

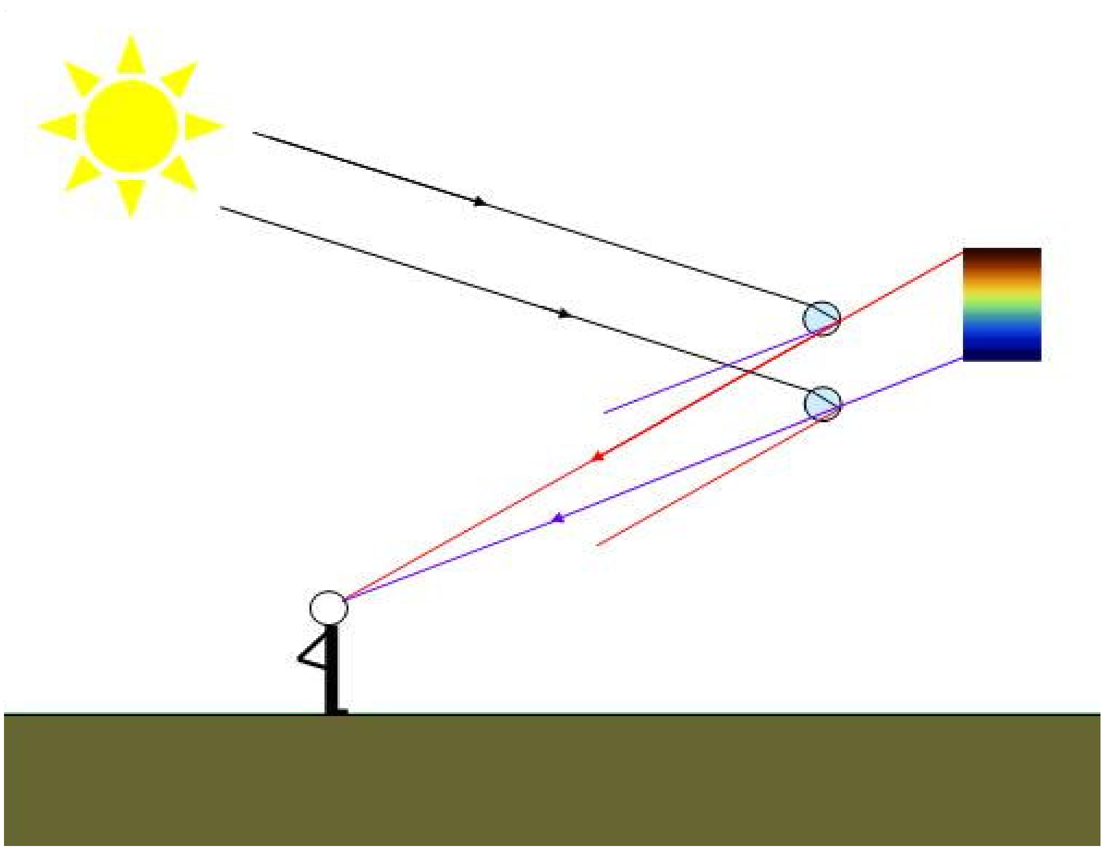


Because violet light has more energy, it takes longer to interact with the glass. As such, it is slowed down to a greater extent than a wave of red light, and will be bent to a greater degree. Note how the prism refracts light twice, once on each face as the light passes through. This accounts for the order of the colors that we see in a rainbow. It is also what gives a diamond the rainbow fringes that make it so pleasing to the eye.

The process of making the rainbows we see in the sky combines the properties of reflection and refraction within a water droplet. Here is how it works:

1. Light from the sun enters the water droplet and is refracted within the droplet.
2. The refracted light is then reflected off the back of the water droplet.
3. The reflected light exits the front of the water droplet and is again refracted, thus further separating the various colors of white light into its red, green and blue components.





From the above illustration it becomes apparent that two things must be in place for you to see a rainbow: 1) the sun must be at your back and 2) the raindrops must be in front of you.

(NOTE: The above explanation is sufficient for most elementary grades, however it is possible that students will come up with some insightful questions about this process. You, as the teacher, should recognize that there is a lot more going on within this process. For example, not all of the incoming light enters the water droplet; some of it is reflected off the front of the droplet. In addition, not all of the light reflects off the back of the water droplet; some of it will pass through the back of the droplet. As the light exits the droplet, some of it is again reflected inside the droplet. Use your discretion when talking about these more complex aspects of rainbows; there is no need to go deeper than necessary, but at the same time you do not want to stifle bright students who pose good questions ☺).

Summary

Everything we **see** is a product of, and is affected by, the nature of light. Light is a form of energy. Our eyes are designed to detect that energy within frequencies that we call visible light. Intricacies in the wave nature of light explain the origin of color, how light travels, and what happens to light when it encounters different kinds of materials.

Links:

Turtle guy teaching about primary colors.

http://www.sanford-artedventures.com/play/color1/color1.html

Activities:

Making colors with PowerPoint (using primary colors to produce secondary colors)

Looking closely at your monitor (increasing pixel sizes and resolution to demonstrate color by addition)

Making colors with food coloring (mixing drops of food coloring to make colors by subtraction).

Making a rainbow (using a glass of water, a mirror, and a flashlight to make a rainbow).

CD rainbows (looking at the rainbow pattern in a CD and explaining how it occurs).

The disappearing beaker (using refraction to make a beaker seem to disappear. NOTE: could also use an eye-dropper and a glass glass from the making rainbows activity).